Integration of Pneumatic Technology in Powered Mobility Devices

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Advances in electric motors, electronics, and control systems have enhanced the capability and drivability of electric power mobility devices over the last 60 years. Yet, battery technologies used in powered mobility devices (PMDs) have not kept pace. Recent advances in pneumatic technology, primarily the high torque, low speed design of rotary piston air motors, directly align with the needs of PMD. Pneumatic technology has advantages over battery-powered technology, including lighter weight, lower operating costs, decreased environmental impact, better reliability, and increased safety. Two prototypes were created that incorporated rotary piston air motors, high-pressure air tanks, and air-pressure regulators. Prototype 1 was created by modifying an existing electric PMD. Range tests were performed to determine the feasibility of pneumatic technology and the optimal combination of components to allow the longest range possible at acceptable speeds over ideal conditions. Using a 1.44 L air tank for feasibility testing, prototype 1 was capable of traveling 800 m, which confirmed the feasibility of pneumatic technology usage in PMDs. Prototype 2 was designed based on the testing results from prototype 1. After further optimization of prototype 2, the average maximum range was 3,150 m. Prototype 2 is up to 28.3% lighter than an equivalent size electric PMD and can be fully recharged in approximately 2 minutes. It decreases the cost of PMDs by approximately $1,500, because batteries do not need to be replaced over the lifetime of the device. The results provide justification for the use of pneumatic technology in PMDs.
Key words: *air, wheelchair, prototype, scooter*

Powered mobility devices (PMDs) have used batteries for their energy source since George Klein invented the first electric wheelchair in the 1950s.[1] Numerous advances in electric motors, electronics, and control systems have enhanced the capability and drivability of PMDs.[2-6] Yet, advancements in battery technologies have not progressed at the same pace.

Prior to the invention of gel-cell lead-acid batteries, wet-cell lead-acid batteries were used in PMDs. Due to the need to pay careful attention to their electrolyte levels and their hazardous nature, they were replaced by gel-cell or sealed lead-acid batteries. These batteries are now the most common type of batteries used in PMDs. They require less maintenance and are safe for airline travel.[7,8] Other types of batteries that have been used with PMDs are nickel-cadmium and nickel-zinc. These batteries offer higher energy densities and are lighter weight when compared to lead-acid batteries, but they are much more expensive[8] and need to be replaced more frequently. Batteries have the tendency to lose capacity if they are only partially discharged for several charge and discharge cycles. It is then necessary to nearly completely discharge and recharge the batteries to restore their capacity. This is called *battery memory*. Nickel-cadmium and nickel-zinc batteries demonstrate a stronger memory effect compared to lead-acid batteries, therefore they are often connected to a control circuit to optimize charging.[8] One study on battery performance found a wide difference in performance over time due to the charge capacity of the batteries becoming unbalanced; another study found the quality and performance of battery chargers to be inconsistent.[7,9] All of these factors affect the performance of the PMD over the lifetime of the device.

Lead-acid batteries can be hazardous and are increasingly costly and difficult to recycle.[10] Annual disposal of PMD batteries is a cost and environmental protection issue.[11] The battery

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Top Spinal Cord Inj Rehabil 2017;23(2):120–130

www.thomasland.com

doi: 10.1310/sci2302-120

maintenance intensity of PMD systems is critically high: charging time (5-8 hours), battery disposal, electrical socket repairs, fire risks, hazardous out-gassing, and electric shock danger make it imperative to investigate alternatives.[12] The need for new power sources, power management systems, and drivetrains for PMDs has been noted in several reports and studies.[10-14] Even though advances in battery technology have been made in hybrid and electric-powered vehicles, the technology remains expensive and presents numerous safety issues for PMD usage.[15] For instance, the lithium-ion technology used in many hybrid and electric vehicles has energy densities twice that of nickel-cadmium and is low maintenance, slow self-discharging. Lithium-ion batteries require protection circuits that monitor the temperature and voltages of each cell to maintain safe operation.[16,17] Despite the advantages of lithium-ion batteries, issues regarding their safety, reliability, compatibility, and cost have prevented their usage in PMDs.[18-20]

To further advance technologies in PMDs, other sources of energy need to be considered. One possibility is compressed air. Air-powered vehicles have been in existence for over 200 years. In the 1800s, locomotives were the first air-powered vehicles; they were powered by the Mekarski air engine, the Robert Hardie air engine, and the Hoadley-Knight pneumatic system. The inventor of the first air-powered car is unknown; numerous individuals claim to have done so in the 1920s and 1930s.[21] In 2012, Tata, an Indian carmaker, claimed that their Air Car would go into production and be one of the cheapest and simplest cars on the road.[22] However, commercialization of the product was delayed for fine-tuning. As recently as 2015, Tata planned to work with Motor Development International (MDI) to make a version of MDI's AirPod available for purchase in Hawaii.[23] As of July 2016, the AirPod has not gone into production. Experts suggest its unavailability is due to its limited range and the lack of infrastructure to recharge the compressed air tanks.[22] Although these 2 issues are also concerns when using compressed air in PMDs, previous research has shown that most PMD users travel short distances over the course of a day and much of that travel is indoors.[24-26] The installation of a supportive infrastructure can be justified by the increased reliability and lower maintenance costs of pneumatic systems compared to electric power systems for both industrial and personal use. These 2 factors should drive the industry toward replacing electric PMDs with pneumatic PMDs. The numerous advantages that pneumatic systems provide over electronic systems justify an investigation of their usage in PMDs. From their potential to allow users to interact with wet environments such as beaches and water parks to their improved transportability because of the decreased weight, pneumatic PMDs can revolutionize the mobility device industry.

In this study, 2 prototypes were created to investigate whether pneumatic technology in PMDs is an alternative to current electric technology. Prototype 1 was created by replacing the electrical system of an electric-powered mobility scooter with the pneumatic system. This served as a testbed to determine the optimal configuration of parameters and components through performance and stability tests. Prototype 2 consisted of a custom-designed aluminum frame and incorporated the findings from testing of prototype 1. In this article, specifications of prototype 2 are compared to specifications of similar electric-powered mobility devices.

Methods

Prototype design and development

Prototype 1

Prototype 1 (**Figure 1**) was developed by installing a pneumatic system consisting of a directional control valve, flow control valve, airline tubing, and pneumatic motor into an electric mobility scooter frame. The original electronic system including 2 batteries, electric motor, computer, and electrical wiring was removed. The directional control valve allowed the device to be driven forward or backward while the flow control valve acted as a speed control by restricting the airflow to the pneumatic motor. The same electric mobility scooter frame was used for the 3- and 4-wheel versions of prototype 1. As a result, the prototype could either be one or the other as

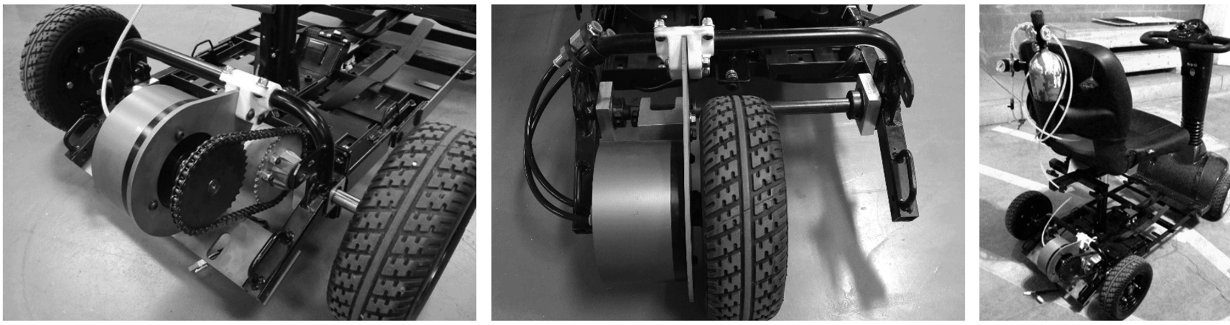

Figure 1. Prototype 1: 4-wheel configuration rear (left), 3-wheel configuration rear (center), and 4-wheel configuration (right).

needed. In the 4-wheel version, the original drive system was replaced with a limited slip differential and 36-tooth sprocket that was connected to the pneumatic motor via a chain and second sprocket (**Figure 1**). In the 3-wheel version, the limited slip differential, sprockets, and chain were removed and the tire was directly mounted to the pneumatic motor output shaft (**Figure 1**).

Prototype 2

Prototype 2 was developed to further enhance the capabilities of the prototype through the design of a custom aluminum frame. We determined the optimal configuration of components by testing prototype 1 and incorporated these findings into prototype 2. Prototype 2 was to be 20% lighter in weight compared to a similar electric mobility scooter, have a maximum user weight of 100 kg, have interchangeable seating systems, and be water resistant. Additional features included a modular front steering mechanism, no electronics, and a single, easily accessible charge port.

Prototype testing

Prototype 1 feasibility testing setup and procedure

Feasibility testing using the 4-wheel version of prototype 1 was performed to determine whether the prototype was capable of traveling a reasonable distance on a fixed amount of air. Reasonable distance was defined as traveling at least 500 m over a flat surface using a 1.44 L tank pressurized to 310 bar. This test was performed using the Bibus EasyDrive PMO 1800 motor,[27] 6.35 mm diameter airline tubing, 6.21 bar operating pressure, and 1:1 gear ratio. The prototype was driven at 1.34 m/s over a flat surface until the 1.44 L tank was empty and the prototype came to a rest.

Prototype 1 range testing setup

After confirming feasibility, the 2 configurations of prototype 1 were tested to calculate the range the prototype could travel under ideal conditions. In addition to the 2 scooter configurations, we tested different size pneumatic radial piston motors: Bibus EasyDrive PMO 1800 and Bibus EasyDrive PMO 3600[27]; different size airline tubing: 6.35 mm and 9.53 mm diameters; different operating pressures: 6.21 and 8.27 bar; and different gear ratios: 1:1, 1:1.2, and 1.2:1. The different gear ratios were achieved by installing 36-, 43-, and 30-tooth sprockets to the motor output shaft, respectively.

These tests were performed on a multidrum testing mechanism typically used for the International Organization for Standardization (ISO) testing for wheelchairs.[28] A 100 kg test dummy was secured to the seat of the prototype to simulate the typical usage of the mobility device when traveling with a user. The slats on the multidrum were removed to simulate a flat, smooth surface, and the multidrum was disconnected from its power source. The velocity of the wheels was measured using a tachometer (Mitutoyo PH-200LC),[29] and the airflow rate was measured using a digital flow meter (SMC, PFMB7501-N04-A).[30] Constant operating pressures of 6.21 and 8.27 bar were tested via a constant supply from the laboratory air source.

Table 1. Component configurations tested using prototype 1

Test	No. of wheels	Motor	Tubing, mm	Pressure, bar	No. of teeth
1	4	1800	6.35	6.21	30
2	4	1800	6.35	6.21	36
3	4	1800	9.53	6.21	30
4	4	1800	9.53	8.27	30
5	4	1800	9.53	6.21	36
6	4	1800	9.53	8.27	36
7	4	3600	6.35	6.21	30
8	4	3600	6.35	8.27	30
9	4	3600	6.35	6.21	36
10	4	3600	6.35	8.27	36
11	4	3600	9.53	6.21	30
12	4	3600	9.53	8.27	30
13	4	3600	9.53	6.21	36
14	4	3600	9.53	8.27	36
15	4	3600	9.53	6.21	43
16	4	3600	9.53	8.27	43
17	3	3600	9.53	6.21	Direct drive
18	3	3600	9.53	8.27	Direct drive

Prototype 1 performance testing procedures

The range testing procedure involved driving the prototype forward while adjusting the flow control valve such that the desired velocity of the PMD wheels was achieved. PMD wheel velocities started at 0.1 m/s and increased in increments of 0.1 m/s until the airflow rate reached 210 L/min (the limit of the digital flow switch) or until the maximum speed of the PMD was reached. Airflow rates at each of the PMD wheel velocities were recorded and later entered into a spreadsheet for data analysis. Each test consisted of changing a single component or parameter and repeating the testing procedure. A breakdown of the tests performed for each of the component configurations is shown in **Table 1**. In addition to the range testing, dynamic stability testing was performed as described in ISO 7176-2: Determination of Dynamic Stability.

Prototype 1 range calculations

Estimated traveling ranges were calculated from the range testing results using a PMD with 24.94 cm wheel diameter (prototype 1 wheel diameter) and two 9 L HPA tanks (common scuba tank volume) at a pressure of 310 bar. Calculating the estimated ranges using 2 HPA tanks was chosen due to the size of the tanks and the limited space for them. The estimated ranges of each of the different components and parameters were compared to determine the optimal configuration for the greatest traveling range at the target traveling speed of 1.4 m/s (average human walking speed).

Prototype 2 performance testing procedures

Range testing of prototype 2 was performed by driving the prototype around an indoor, rectangular track as described in ISO 7176-4: Energy Consumption. Testing started with the scooter traveling at a velocity of 1.4 m/s and was stopped when the prototype's velocity dropped below 0.5 m/s. The prototype was driven around the track in either the clockwise or counterclockwise direction for 5 laps; the direction of the prototype was then reversed and driven for another 5 laps. This process was repeated until the minimum threshold velocity was reached. Three different configurations were tested, 3 times each to obtain an average. The testing configurations were 1 scuba tank (9 L), 2 scuba tanks (18 L), and 2 scuba tanks with the addition of a 1.44 L tank (19.44 L) as an expansion chamber. The slope climbing capability of prototype 2 was tested using 2 scenarios: approaching a 10° slope at a velocity of 1.4 m/s, and starting from a stopped position at the bottom of the slope. The velocity of the prototype had to be a minimum of 0.5 m/s after traveling 10 m up the slope to pass the test.

Results

Prototype 1

Feasibility and performance testing

In the feasibility test using the 4-wheel version of prototype 1, it traveled 800 m with a 1.44 L air tank; this led us to the conclusion that the use of pneumatic technology in PMDs is feasible. Therefore, testing continued to determine the optimal configuration of components and parameters. The calculated results for the estimated range versus velocity for prototype 1 are presented in **Figure 2** for the PMO 1800 motor and **Figure 3** for the PMO 3600 motor. For both motor sizes, there is a negative linear trend such that as velocity increases, range decreases. We found that higher gear ratios and larger airline tubing diameters increased maximum velocity and range of values; there was no change in velocity or range capability between operating pressures. During dynamic stability testing, the prototype was capable of climbing the slopes at a higher velocity using the higher operating pressure.

After analyzing each of the configurations, we determined that a 3-wheel scooter with the PMO 3600 motor, gear ratio of 1:1.2, 9.53 mm tubing, and 8.27 bar operating pressure was the optimal configuration that provided the greatest range when traveling at a speed of 1.4 m/s. However, with this optimal configuration, the 3-wheel version of prototype 1 failed the dynamic stability testing. As a result, we used the 4-wheel version of prototype 1 as the basis for the design of prototype 2.

Prototype 2

Prototype design

A 4-wheel mobility scooter was designed with a custom frame made from 25.4 mm diameter, 1.65 mm wall thickness, and 6061-T6 aluminum tubing at a weight of 2 kg (**Figure 4**). The design included a modular front steering assembly for simplified maintenance, easily removable seat allowing for

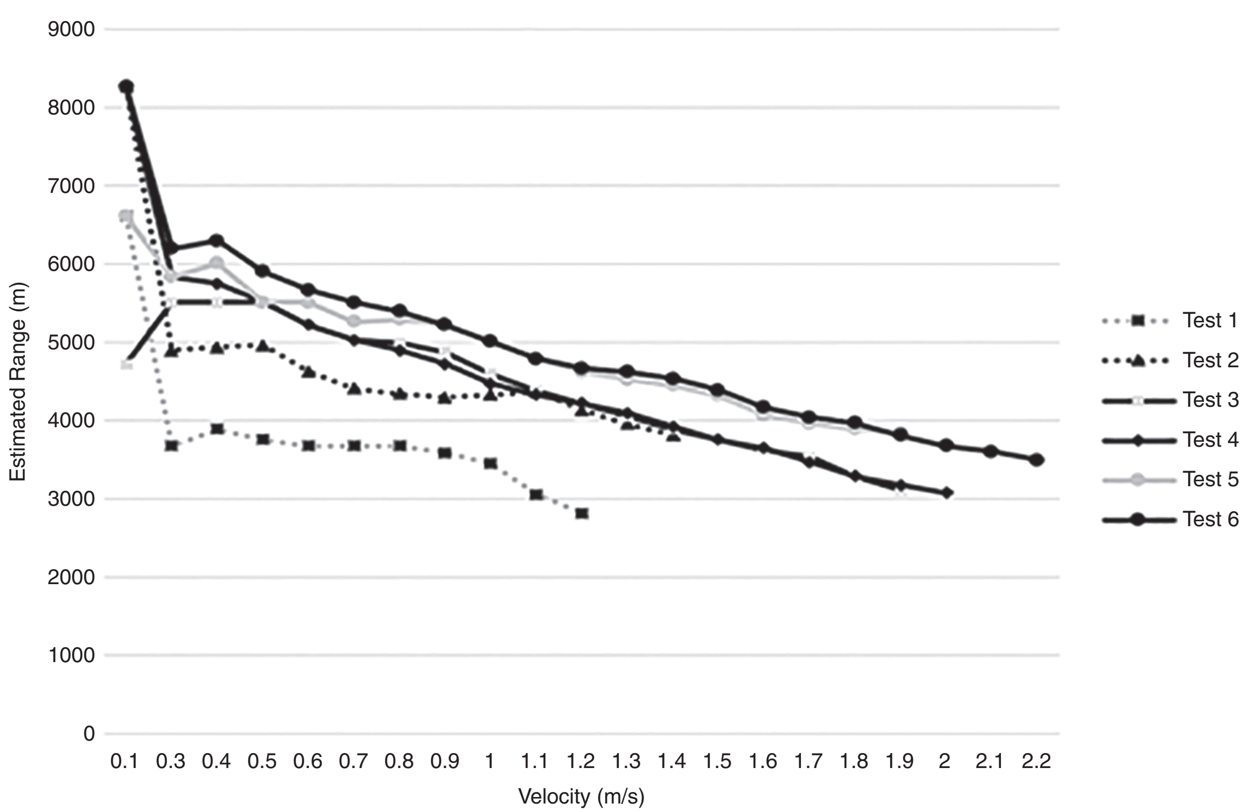

Figure 2. PMO 1800 motor test results.

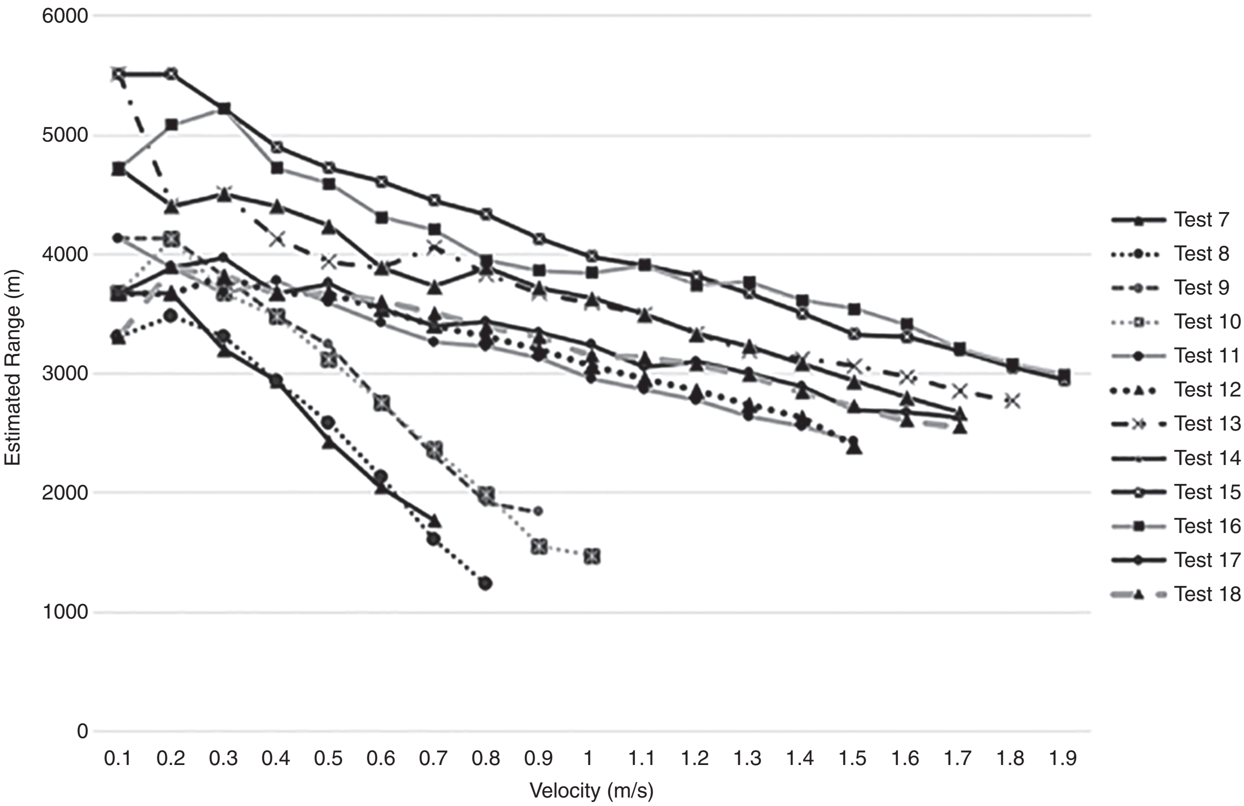

Figure 3. PMO 3600 motor test results.

Figure 4. Prototype 2 aluminum frame (left); prototype 2 (right).

multiple seat types, and an easily, accessible charge port to recharge all of the tanks at once. The completed design of the prototype 2 is shown in **Figure 4**.

Performance testing

The results of the range testing for prototype 2 revealed that the scooter can travel an average of 1267 m using 1 scuba tank (9 L), 2762 m using 2 scuba tanks (18 L), and 3150 m using 2 scuba tanks and a 1.44 L tank (19.44 L) as an expansion chamber at an ambient temperature of 21°C. In the slope climbing tests, prototype 2 passed both scenarios when using the optimal configuration of components determined from testing prototype 1. When the gear ratio was increased to 1:1.4, the prototype was unable to pass either slope testing scenarios. As a result, the prototype's gear ratio was set to 1:1.2.

Pneumatic vs electric PMD

The specifications of prototype 2 and other similar electric PMDs are presented in **Table 2**. Electric PMD 1 and PMD 2 are 4-wheel versions of the Pride Mobility Victory 10[31] and Golden Companion II,[32] respectively. The specifications of prototype 2 were measured using the actual device, whereas the specifications of electric PMD 1 and PMD 2 were taken from the manufacturers' websites. The pneumatic PMD is similar in size and maximum speed to both electric PMDs. In terms of weight, the pneumatic PMD is similar to electric PMD 1 but is 28.3% lighter than electric PMD 2. The pneumatic PMD has significantly less charge time and maximum range per charge than either electric PMD. However, range per charge time for the pneumatic PMD is much greater at 1.575 km/min versus an average of 0.059 km/min of the 2 electric PMDs.

Discussion

The design and testing of prototype 2 indicates that pneumatic technology is a viable replacement for electric PMD. Pneumatic technology solves many of the major issues experienced with electric PMDs and can decrease the overall lifetime costs of the device. Based on Medicaid and Medicare's replacement guidelines, PMDs are expected to have at least a 5-year lifetime.[33] One major issue with electric PMDs is the frequency that repairs are needed. In one study, a survey that included power wheelchair users found that of the 239 power wheelchair participants, 65.6% (157/239) needed at least one repair within the 6-month period prior to participation in the study. Forty-nine percent (77/157) of the 65.6% experienced more than one adverse consequence, in which 24.2% (38/157) of the individuals were left stranded. The study also found that the most frequent repairs for power wheelchairs were to the electrical, power, and control systems.[34] When repairs are needed to these systems, they are typically performed by a mobility device supplier; this can be a lengthy process. Many of the components of a pneumatic PMD are widely available and affordable and can be fixed by anyone who is technically skilled. Pneumatic PMDs are designed for years of use with little maintenance. This decreases the possibility of the user being without a PMD for a long period of time.

Some common concerns when using pneumatic systems are noise and safety. The noise of a pneumatic system is generated when the air is exhausted out of the pneumatic motor. Typical pneumatic motors

Table 2. Pneumatic- and electric-powered mobility device (PMD) specifications

Device	Pneumatic PMD	Electric PMD 1	Electric PMD 2
Size, cm	124 x 58	119 x 57	121 x 61
Weight, kg	61.1	62.4	85.3
Charge time, min	2[a]	480[b]	360[b]
Max speed, m/s	2.24	2.35	2.01
Max range per charge, km	3.15	25	24

[a]Depends on charging method.
[b]Manufacturer minimum recommended charge time.

have noise levels that average 77 dB. These levels increase with speed and are greatest when under no load. The Bibus pneumatic radial piston motor used in our prototypes has a noise level of about 60 dB,[27] similar to that of a pair of electric-powered wheelchair motors that operate at 58 dB. These levels can further be decreased with the addition of a muffler. In terms of safety, pneumatic components use no hazardous materials and meet both explosion protection and machine safety requirements because they do not generate magnetic interference.[35]

The following potential charging methods describe the ranges of time required to charge pneumatic PMDs. Pneumatic PMDs are "charged" (air tanks filled) via an air compressor that is capable of filling the tanks up to a pressure of 310 bar. The compressor is connected to the PMD via a quick disconnect connection, similar to how electric PMDs are plugged in to charge. The length of time for a full charge is based on the method of recharging. The first method is to have a "filling station" that consists of a large storage tank that is hooked up to a compressor that constantly maintains the storage tank pressures at 310 bar. Then, filling the tanks is as simple as connecting the PMD to the storage tank and opening a couple of valves to allow air to transfer from the storage tank to the tanks on the PMD. This method takes approximately 2 minutes to fill the tanks from empty. The second method is identical to the first but with the absence of the storage tank. The pneumatic PMD would be connected directly to the compressor as described above. The charge time for this method depends on the size of the compressor. For instance, the Bauer Junior II has an air flow rate of 100 L/min.[36] At that rate, it takes approximately 90 to 120 minutes to completely fill all 3 tanks from empty. The third method would be to have one large or a number of small tanks that are filled to 310 bar. These would act as the storage tank described in method one. The pneumatic PMD could be connected to the tank(s) to recharge. To refill the storage tank(s), a mobile air compressor unit could fill the tanks or a bottle service could be used to pick up the empty tank(s) and replace them with filled tanks. The number of recharges would depend on the size and number of storage tanks. Charging time for this method would be similar to method one, approximately 2 minutes.

Methods 2 and 3 are better suited for in-home charging due to their small footprint. For users who need quicker recharges and require multiple recharges throughout the day due to traveling longer distances, method 3 would best suit their needs. However, method 2 is more suitable for users who do not travel long distances during the day and only need to recharge their device once a day. Method 1 is more like a gas station for vehicles. The filling station has the capability to recharge numerous devices in a short amount of time. This is beneficial in airports, shopping malls, amusement parks, hospitals, and nursing homes.

PMDs typically have a small wheelbase to allow them to fit through doors and be maneuverable indoors. As a result, the size of the air tanks is limited; thus to achieve the range that PMD users require, HPA tanks similar to those used by firefighters and scuba divers are the best option because of their size and safety record. HPA tanks have the capability to be filled up to 310 bars. The typical compressor found at a local hardware store is not capable of reaching such pressures. However, these compressors are commonly available at sporting goods stores that charge paint-ball tanks, at dive shops, and at fire or emergency medicine technician stations. Air compressors that meet the necessary specifications to fill HPA tanks typically costs between $250 and $1,500 and can be operated for up to 10 years or more with little or no maintenance.[37] HPA tanks cost from $50 to hundreds of dollars and need to be hydro-tested and recertified every 3 to 5 years at a cost of approximately $20 per tank.

When filling HPA tanks to pressures up to 310 bar, power consumption versus pressure has a linear relationship. The potential energy of 9 L of air at 200 bar is 953.7 kJ and at 310 bar is 1600 kJ.[38] Using the Bauer Junior II compressor with a 2.2 kW motor,[36] the energy consumption to fill a 9 L tank to a pressure of 200 bar is 2340 kJ in a completion time of 17.75 minutes (0.3 hours) while filling a tank to 310 bar requires 3960 kJ in a time to fill of 30 minutes (0.5 hours). The resulting efficiency of the Bauer compressor is approximately 41% when filled to either pressure. The energy consumption when charging electric PMDs can be as high as 10,370 kJ when considering the maximum charge time of 8 hours using a 120 V charger operating at 3 A. When comparing the energy consumption between electric and pneumatic systems, a pneumatic system can be recharged 2.2 more times when filling the system to 200 bar and 1.3 more times when filling to 310 bar.

The range of devices powered by compressed air is based on the pressure, volume, and temperature of stored air on the PMD. Air volume can be increased by increasing the pressure inside the air tank, raising the temperature (eg, through an expansion chamber), or increasing the air tank size. As the air leaves the main tanks, it is fairly cold. In addition to using the expansion chamber to raise the air temperature, the air lines could also be routed through the seat cushion. Thus, the cold air would lower skin temperatures while the individual's body heat would raise the air temperature. In the end, the warmer the air, the further distance the device can travel. Lower skin temperatures may also reduce the risk of pressure ulcers.

The average electrical PMD battery lasts 6 months to 1 year. Battery lifetimes are based on numerous factors including battery size/type, charging frequency, level of daily discharge, and daily usage. The range of travel of electric PMDs is variable based on the terrain traversed and driver habits. Traveling up slopes and at higher speeds tends to decrease the range of a PMD. Therefore, batteries will need to be replaced a minimum of 5 to 6 times over the expected lifetime of the device. Battery replacements can cost from $100 to $500 depending on the type of PMD. Thus, pneumatic technology may result in a savings of approximately $500 to $2,500 over the lifetime of the device, when considering the batteries alone.

Pneumatic systems have the potential to provide rapid, nearly unlimited recharging; lighter weight; lower operating cost; and smaller environmental impact.[39,40] With the growing availability of lightweight, portable HPA tanks, a pneumatic drive system could strengthen individual independence and mobility and lower health care and institutional costs. The recent availability of low-cost, efficient rotary piston air motors has made HPA a practical alternative to electric power for PMDs. Future work for pneumatic technology may also be integrated into other PMDs such as power wheelchairs (**Figure 5**) or power-activated power-assist wheelchairs. The overarching goal is to remove the need for batteries and replace them with a more user and environmentally friendly alternative.

Pneumatic systems are also well suited for use in PMDs because of their resilience to environmental hazards such as dirt, heat, and moisture.[41,42] Pneumatic powered systems have a clear advantage over electric-powered systems in the presence of water or moisture or in environments where there are fire/explosion risks (eg, oxygen rich environments). HPA-powered PMDs have the potential to open up avenues for independent mobility on beaches, in amusement/water-parks, and in other wet environments. Moreover, in environments with high relative humidity, an HPA-powered PMD should have much higher reliability and longevity than an electric-powered PMD.[43] This could be an important contribution to powered mobility in less-resourced countries. An HPA-driven PMD could support community integration by increasing reliability and availability of the PMD. It could also promote participation in many activities of daily living through improved transportability due to the PMD being lighter in weight.[24,44]

Figure 5. Power wheelchair concept.

Conclusion

The justification for investigating pneumatic systems in power mobility devices is validated based on the findings from previous studies that mobility device users typically travel an average 2,524.7 m in a day.[24,25,44] The range tests of prototype 2 prove that the device is capable of achieving 3,150 m on a single charge. The numerous advantages of pneumatic-powered mobility devices versus electric-powered mobility devices provide further optimism. Further development and integration of the technology into mobility devices could transform the mobility device industry by decreasing costs, improving safety, decreasing environmental impact, improving reliability, and enhancing the lives and quality of life of PMD users.

Acknowledgments

The authors report no conflicts of interest.

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